Toward an effective centrality trigger in pp collisions at LHC

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We investigate the impact of very strong small x gluon fields in colliding nucleons at LHC energies on the interaction of valence quarks. We find that in the range of small impact parameters, which contribute significantly to the production of heavy new particles, several of the valence quarks receive large transverse momenta, exceeding 1 GeV/c. This results in a suppression of leading baryon production and consequently in an additional energy flow to smaller rapidities. We suggest several triggers for centrality in pp collisions which allow one to study the propagation of partons through gluon fields of a strength comparable to the ones encountered in heavy ion collisions at the LHC.

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It is now widely realized that a fast increase of gluon densities at small x should result in the onset of the black disk regime (BDR) of interactions of partons up to rather large virtualities (transverse momenta). In the BDR a parton gets a large and with energy increasing transverse momentum when passing through the gluon field ($\sim Q_s$ in the color glass condensate models, for a recent review see [1]). In the BDR regime, the parton also loses a finite fraction of its energy, which allows one to explain the pattern of leading pion production observed at RHIC in deuteron-gold collisions[2]. Gluon densities in the nucleon, at small transverse distances ρ from the center, are comparable to those in nuclei at small ρ for the same energies. In particular for $\rho = 0$, and $A \sim 200$,

$$\frac{G_N(x, Q^2, \rho = 0)}{G_A(x, Q^2, \rho = 0)} = \frac{2B}{\gamma_A \rho_0 2R_A} \geq 0.5, \qquad (1)$$

where ρ_0 is the nuclear matter density. Here we took an exponential shape for the gluon distribution in the nucleon corresponding to the two gluon form factor of $\exp(-Bt/2)$ (a dipole fit to the two gluon form factor gives an even larger ratio) and neglected the leading twist gluon shadowing which suppresses $G_A(\rho)$ by a factor of $\gamma_A(\rho)$. Since s_{NN} for pp and for heavy ion collisions at the LHC differs by a factor of 6 and the gluon density depends on s as $s^n, n \sim 0.2$ for the virtualities of a few GeV^2, we find that the gluon densities in the two cases are similar. Hence up to $\rho \sim 0.6$ fm the gluon density in a nucleon is comparable to the *average* gluon nuclear density in heavy ion collisions (and larger than the gluon densities in heavy ion collisions at RHIC). At larger ρ the nucleon gluon density decreases rapidly.

There are two challenges: (i) to device a trigger which would select pp collisions at small impact parameters ($\langle b\rangle \leq \langle \rho\rangle \sim 0.6$ fm) in order to investigate high gluon density effects in pp collisions at densities comparable to AA collisions, and (ii) to account for high gluon density effects in central pp collisions which give the dominant contribution to the production of heavy particles like the Higgs, or in SUSY.

Since the smallest x_2 gluons are resolved by large x partons in the projectile regions - $x_2 \sim 4k_t^2/xs \sim 10^{-7}$ for $x \sim 0.3$ and $k_t = 1$GeV/c - we expect the strongest effects of the high density gluon fields for the interaction of valence quarks which should influence the structure of the final states in the fragmentation region. Even larger effects are present for the interaction of the leading gluons due to a factor of 9/4 stronger interaction in the gluon-gluon channel. These effects are likely to be manifested at smaller rapidities since gluon distributions have a much softer x distribution than quarks. (The current MC models usually neglect hard QCD effects in this kinematic region focusing on hard QCD dynamics in the central region.)

For a pp collision at a given impact parameter b, individual partons of one nucleon can pass at a range of transverse distances ρ from the second nucleon and hence encounter significantly different local gluon densities (see Fig.1). In this paper we analyze the effects of the valence quark interaction with small x gluon fields taking into account the geometry of the collisions. This will allow us to determine how frequently valence quarks in pp collisions at different impact parameters b, experience hard collisions in which they obtain a large transverse momentum. Based on this study we propose a series of centrality triggers which allow to select collisions at much smaller impact parameters than in generic inelastic events and hence will provide an opportunity to study the high gluon field effects in pp collisions. We also suggest that the pp collisions leading to production of new particles like the Higgs boson should be accompanied by a significantly stronger flow of energy from the fragmenta-

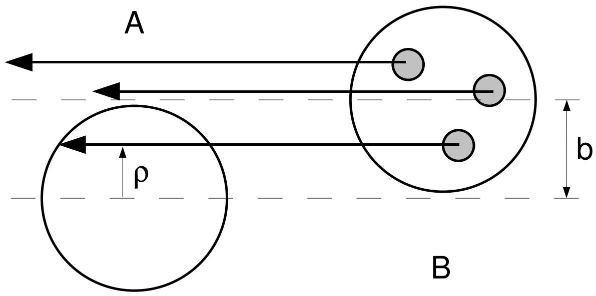

FIG. 1: Schematic view of the collision geometry.

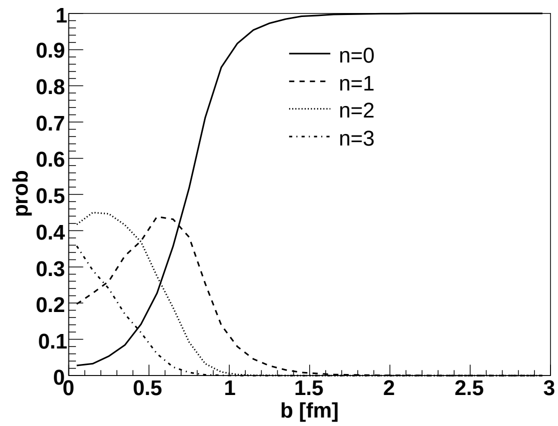

FIG. 2: Probability for the different classes of events with n quarks struck at a given impact parameter b.

tion regions to smaller rapidities than in generic inelastic collisions.

Description of the model. To model the fragmentation region in pp collisions we take a simple model for the three quark wave function with the distribution of quarks over transverse distance from the center given by $\exp(-A\rho_i^2)$ with $<\rho^2>\sim 0.3fm^2$ matched to describe the distribution of the valence quarks as given by the axial nucleon form factor. Accordingly, the event generator produces the values of ρ_i for three quarks which are not correlated. Note that one does not expect a very strong correlation between ρ's due to the presence of additional partons in the wave function (gluons, $q\bar{q}$ pairs). Nevertheless we checked that a requirement $|\sum_{i=1}^{3}\vec{\rho_i}| \leq 0.1$ fm does not change results noticeably. Hence we neglect possible correlations in ρ between valence quarks. We also assume that there are no significant transverse correlations between small x ($x\sim 10^{-5}$) partons. This assumption is based on the presence of diffusion in ρ in the small x evolution which should wash away whatever correlations may be present at large x ($x>0.1$). (For a discussion of the evidence for such correlations see [3].)

When computing the momentum fractions of the quarks, we need to know the virtuality at which the quarks are resolved. Since the latter quantity is not known beforehand, we generate $x_{B,i}$ and $\vec{\rho_i}$ from $dx/x = const.$ and $d\rho = const.$ distributions. The selection according to the structure functions and the form factor is done in the end, after specifying Q_s^2, via rejection. For a given impact parameter $\vec{b}$ and relative positions of the quarks $\vec{\rho_i}$ in the projectile, we estimate the density within the color glass condensate approach. So we need to know the saturation scale in the target for the three valence quarks.

$$Q^2 = Q_s^2(x_A, |\vec{b}+\vec{\rho_i}|), \tag{2}$$

with $x_A = Q^2/(sx_B)$. The saturation momentum is parameterized as

$$Q_s^2(x_A,\rho) = Q_{s,0}^2\left(\frac{x_0}{x_A}\right)^{\lambda} F_g(x_A,\rho;Q_s^2)/c_F, \tag{3}$$

where c_F normalizes the density. We choose $x_0 = 0.01$, $Q_{s,0}^2 = 0.6$ GeV^2 and $c_F = F_g(x_0,0;Q_{s,0}^2)$ such that the saturation momentum in the center of the target at $x_A = x_0$ is just $Q_{s,0}^2$. The implicit definition for the saturation scale in eq. (3) is solved by a simple iteration, the expression converges after a few steps. Finally, the whole configuration is accepted with the probability

$$p \sim \rho F_g(x_B,\rho;Q_s^2)x_B f_{\rm GRV}(x_B,Q_s^2)\ , \tag{4}$$

where $xf_{\rm GRV}$ are standard GRV structure functions of the proton, and the two-gluon form factor at high momentum fraction x_B describes the spatial distribution of the valence quarks. The actual transverse momentum kick is then drawn from the distribution [4, 5]

$$C(k_t) \sim \frac{1}{Q_s^2\log\frac{Q_s}{\Lambda_{QCD}}}\exp(-\frac{\pi k_t^2}{Q_s^2\log\frac{Q_s}{\Lambda_{QCD}}})\,. \tag{5}$$

We conservatively considered only the case when the BDR is reached for $Q_s \geq 1$ GeV/c and counted only quark interactions in which the quark received a transverse momentum $k_t \geq 0.75$GeV/c. The reason for such a cut is that for such momenta, the probability to form a nucleon with large longitudinal momentum is suppressed, as a minimum, by the square of the nucleon form factor $F_N^2(k_t)$. In the BDR a quark not only gets a large transverse momentum but also loses a finite fraction of its momentum - we neglected this effect in our analysis since it is likely to be on the scale of a 10% energy loss and would not affect our qualitative discussion. We also assumed in the analysis that the gluon densities at small x are not fluctuating significantly for a impact parameters where the BDR holds (this is an assumption usually made in the saturation models where the the small gluon field is treated as nearly classical field). Neglecting fluctuations seems safe for the small x in our analysis, though for

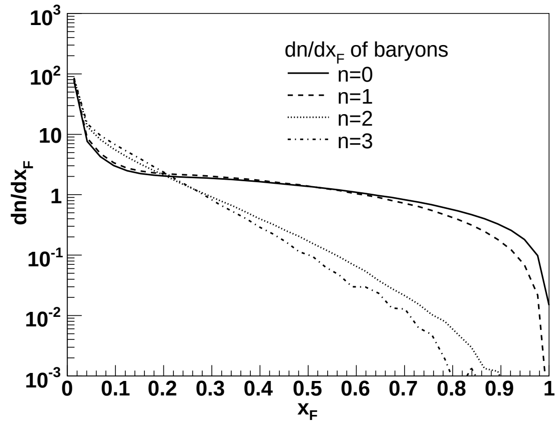

FIG. 3: dn/dx_F distribution of baryons.

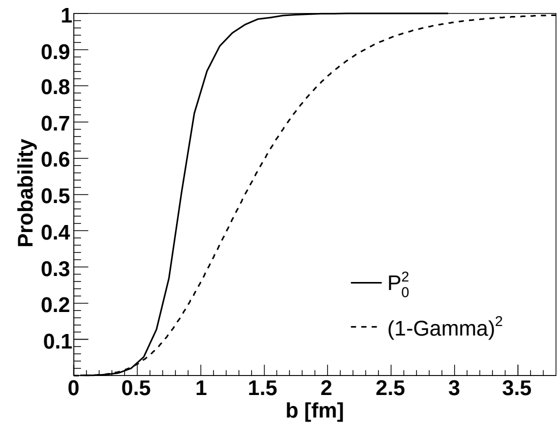

FIG. 4: Probability that no quarks were struck (solid curve as compared to the probability of absence of generic inelastic interaction (dashed curve) as a function of b.

larger x relevant at the Tevatron collider they may be more important.

As a first result, the probabilities P_i for i quarks to interact in the BDR regime (number of "wounded" quarks, N_w) are presented in Fig. 2 as a function of the impact parameter b. Note that for small b interactions $N_w \geq 2$ dominate. In such interactions each quark fragments independently, so the spectra for $N_w = 2$ and $N_w = 3$ should be rather similar and shifted to much smaller x_F than in soft interactions where the spectra of nucleons are known to be flat in x_F in a wide range of x_F. At the same time for $N_w = 1$, the dominant process is likely to be diquark fragmentation which is similar to the soft mechanism. Hence one expects two distinctive shapes of x_F distributions - one with leading baryons ($N_w = 0, 1$) and another with suppressed forward scattering ($N_w = 2, 3$). We implemented the fragmentation of the system produced in the first stage by constructing strings which decay using the LUND method. There are always two strings, drawn between a quark and a diquark from the interacting particles. When a quark of the diquark receives a high transverse momentum, the diquark becomes a system of two quarks and a junction. This has the nice property that one recovers the diquark when the invariant mass between the two quarks is small. The results are plotted in Fig. 3 and are in good agreement with the qualitative expectations discussed above.

The total probability of an inelastic interaction at given impact parameter can be expressed through the impact factor $\Gamma(b)$, which is the Fourier transform of the elastic amplitude, as $1 - |1 - \Gamma(b)|^2$. On the other hand in our model we calculate the probability of inelastic interactions due to the hard interaction of i quarks of one of the nucleons, P_i. Since in the discussed approximation there is no correlation between the interactions in two fragmentation regions for a fixed b the probability that none of six valence quarks will get a kick is $1 - (1 - P_1 - P_2 - P_3)^2$. For a consistency of the model we need that

$$1 - |1 - \Gamma(b)|^2 \geq 1 - (1 - P_1 - P_2 - P_3)^2, \qquad (6)$$

or

$$\Gamma(b) \geq P_1 + P_2 + P_3. \qquad (7)$$

We find that this condition is satisfied for all b (within the uncertainties of the current models for pp elastic scattering at LHC) - see Fig. 4 indicating that hard collisions lead to saturation of the black limit for Γ for small b at LHC energies, while at large b hard interactions give a very small contribution. Hence the model provides a dynamic explanation of $\Gamma(b \sim 0) = 1$ and leads to expansion of the $\Gamma(b) = 1$ region with increase of energy.

Very strong dependence of N_w on b and a strong correlation of N_w with the multiplicity of leading baryons allows one to determine the effectiveness of a centrality trigger based on a veto for the production of leading baryons with $x > x_{tr}$ as a function of x_{tr}. We find than an optimal value of x_{tr} is ~ 0.1. Current configurations of several LHC detectors allow to veto neutron production in this x-range. TOTEM, in addition, allows to veto production of protons with $x_F > 0.8$. Since neutron and proton multiplicities are similar, a one side veto for production of both charged and neutral baryons leads approximately to the same result as a two side veto for neutron production. Accordingly we will give results both for single side veto and for two side veto for both neutral and charged baryons (understanding that the full implementation of the latter option would require certain upgrades of the detectors some of which are currently under discussion).

The results of the calculations are presented in Fig. 5 together with the distribution over b for generic inelastic

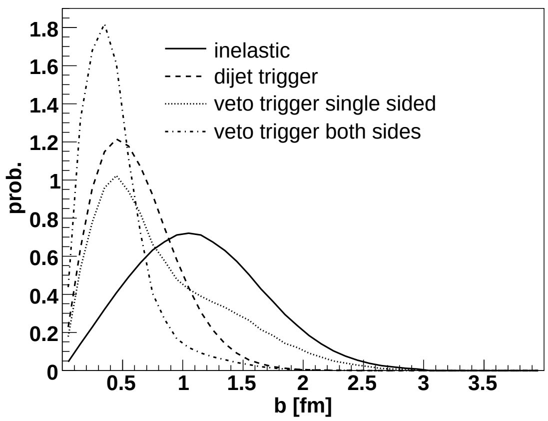

FIG. 5: Impact parameter distributions for inelastic events, the dijet trigger and single and double sided veto-trigger (no baryon in the region $x_F > 0.1$).

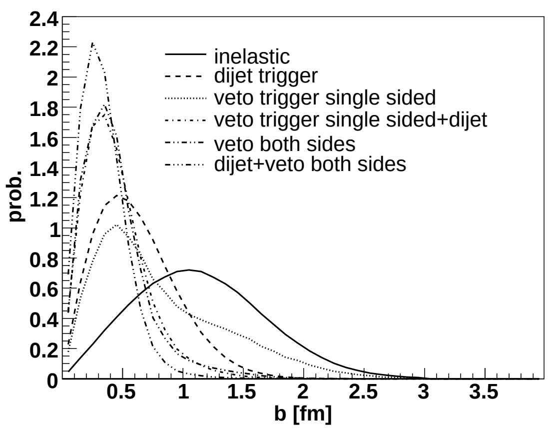

FIG. 6: The combination of dijet and veto trigger gives the best constraints on central events in pp-collisions.

events and the central dijet trigger [6]. We see that the single side veto trigger leads to a centrality similar to that of a the dijet trigger, while a double side veto leads to the most narrow distribution in b. An easy way to check this expectation would be to compare other characteristics of events due to these triggers - one expects for example a progressive increase of the central multiplicity with a decrease of average b.

The most narrow distributions can be achieved by combining two types of the triggers - veto and dijet - Fig. 6. We find that in this case we reach the limit that $\langle\rho_{tr}\rangle = \left(\langle\rho^2\rangle + \langle b^2\rangle\right)^{1/2}$ becomes comparable to $\langle\rho\rangle$ which is the smallest possible average $\langle\rho\rangle$ for pp or DIS collisions.

In line with discussion of Eq. 1 we expect that for our best centrality triggers average gluon densities will be comparable to those in the heavy ion collisions. Indeed, we estimate the average gluon density encountered by the leading partons, and find it larger than the one encountered at central impact parameters in pA collisions at RHIC where BDR holds at least for $p_t \leq 1.5$GeV/c. Further, it is about $\frac{1}{2}$ of the average gluon density in heavy ion collisions at LHC. (However dispersion in the value of Q_s is much larger in the pp case).

We also estimated the effect of a dijet trigger (which is the same selection of impact parameters as for production of heavy new particles). We find that in 16% of these events at least in one fragmentation region no leading baryons would be present with $x_F \geq 0.1$ as compared to a generic case where this fraction is 8%. This should result in a significantly larger flow of energy to central rapidities and strong fluctuations of this flow on an event by event basis. Since the probability of interaction for gluons with $x \geq 10^{-2}$ is at least as large as for quarks with $x > 0.1$ we expect that many of the gluons with these x will also lose coherence with the low transverse momentum partons and will fragment independently further contributing to the energy flow to central rapidities. It is important to investigate how these effect would impact on the various triggers suggested for the searches of the new particles.

In conclusion, we have demonstrated that it will be feasible to trigger on very central pp collisions at the LHC. The high gluon densities encountered by the colliding partons in such collisions facilitate studies of novel QCD effects complementary to heavy ion collisions, such as the p_t broadening of the Z-boson distribution as compared to generic events, multiplicity fluctuations, elliptic flow, etc.

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